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Life Cycle Assessment of Expanded Polystyrene Lightweight Concrete Using Traci 2.1 Methodology

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Abstract

In 2021, the United Nations Environment Programme (UNEP) released a global status report that showed 37% of the world's annual carbon dioxide (CO2) emissions came from the building industry. The same report of UNEP in 2018 states that almost 40% of energy-related CO2 came from the same industry 11% of which is from concrete, this makes concrete the biggest source of CO2 emissions among all building materials. This shows how important reducing greenhouse gas emissions from building materials is, with concrete being one of the most significant contributors, mitigating environmental emissions of concrete by innovating aggregate replacements such as Expanded Polystyrene (EPS) has become one of the potential solutions to this problem. However, there are minimal investigations regarding the life cycle of EPS Lightweight Concrete (LWC). This paper presents the life cycle assessment (LCA) of EPS LWC using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.1 methodology along with its comparison against traditional reinforced concrete, CAB70 LWC, and Polyethylene Terephthalate (PET) concrete. In this study, tables and graphs revealed significant differences on the environmental impact values of four different types of concrete and the result shows that in comparison with traditional reinforced concrete, EPS LWC contributes a significant change in mitigating most of the environmental impact categories. However, it is not the same case with the CAB70 LWC and PET concrete, EPS LWC evidently has higher environmental impact values but the difference was not as significant as that of against traditional reinforced concrete.

Keywords: Expanded Polystyrene, Life Cycle Assessment, EPS Lightweight Concrete, OpenLCA, TRACI 2.1

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1. Introduction

Construction materials contribute a significant amount of carbon dioxide (or carbon footprint) to overall greenhouse gas emissions, and it has been a major problem that is being explored and mitigated to improve the sustainability of the building sector. Numerous local and international organizations, including the United Nations (UN), currently prioritize the energy efficiency and sustainability of buildings. Utilization and advancement of new low-carbon construction materials have already been developed over the past few decades, but the majority of currently used materials, such as masonry blocks and insulating slabs – rock wool and even expanded polystyrene (EPS)– are still old and extremely carbon intensive (Zimele, 2019). Even though EPS is not free from carbon emissions during its life cycle, it is nevertheless employed in construction due to its sustainability advantage and contribution to energy efficiency, durability, and indoor environmental quality improvement (Sulong, 2019).

In recent years, the construction industry has experienced massive changes both in terms of practices and applied technologies. Different applications are being developed and studied for further improvement of existing construction scenarios. However, with continuous innovation, the reserves and natural resources have also been depleting. That is why sustainable approaches are being considered throughout the world. According to Nikbin and Golshekan (Nikbin, 2018), the significance of environmental, economic, technological, and durability considerations in construction has resulted in the rise and development of LWC in recent years, one of the carefully considered types of concrete construction materials in the industry today is EPS and since EPS is widely using, it would be necessary to study its advantages and environmental impacts as it will be used in the construction industry.

Artificial LWA made from environmental waste is a feasible supply of structural aggregate material, especially as concerns about the overexploitation of natural aggregates grow (Demirboga, 2012). Consequently, it is critical to develop a life cycle assessment (LCA) of EPS material to further gather information and find out its impacts to our environment. In this context, LCA is a tool developed as a methodology capable of supporting operations of chosen material by evaluating the environmental impact of products and processes across their entire life cycle and presenting unambiguous scientifically based results (Vieira, 2016).

The LCA also is a scientific method that identifies and quantifies the energy and material uses and releases to the environment to evaluate the environmental influence associated with a product, process, or activity. Furthermore, the LCA approach tries to implement options for environmental improvements (Chau, 2015). According to Hauschild et al. (Hauschild, 2018), LCA is one of the most effective assessment tools for construction professionals in quantifying an infrastructure's ecological effects during its lifetime. That is why LCA is an important methodology that evaluates a material's life cycle.

There are already a variety of EPS applications used in the construction industry, but the uses of EPS are still being thoroughly studied due to its flexibility of use as an aggregate in lightweight concrete (LWC), decorative tile, and moldings or for panel applications (Sulong,

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2019). In terms of modern construction applications such as offshore projects, tall buildings, and long-span bridges, LWC is becoming more common (Jayanth, 2018). Furthermore, the concept of sustainability is becoming more prevalent in engineering construction as it

encompasses all stages of a building's life cycle, including design, construction planning and management, construction work, maintenance, and rehabilitation of structures or infrastructure objects. For a construction sector to divert into a sustainable approach, different considerations are carefully studied (Zavadskas, 2018).

This study aims to evaluate the properties and environmental impact of LWC with EPS beads as an aggregate by means of life cycle assessment (LCA). Specifically, it determines the environmental impact and difference of applying EPS as an aggregate alternative. Examine the difference in LCA outcomes of EPS LWC against traditional reinforced concrete and data gathered from the literature. Also, it analyzes and assesses the environmental impact values gathered from LCA software.

Moreover, the significance of the study includes the construction industry by selecting a sustainable alternative aggregate, and the manufacturer by serving as a guide to support the use of EPS LWC as a construction material in new building designs and promote sustainable products. To the civil engineers, by applying EPS LWC as an alternative in building designs. To the university, this research provides more knowledge with regards to the use of EPS LWC. Then to future researchers, the result of this study will serve as a reference if alike research is to be studied using LCA on LWC.

The study is localized in the new College of Engineering and Architecture (CEA) building of Bataan Peninsula State University-Main Campus and addresses only whether EPS as an aggregate material possesses too many environmental impacts. Moreover, the study only utilizes the EPS material installed in the New CEA building, and other data regarding LWC will be gathered straight from the existing research findings of other authors. Also, the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) 2.1 shall be the only database utilized for this study that is integrated into OpenLCA software. Economic benefits, structural computations, and actual experiments are also not included in this study as lack of laboratory equipment, facilities, resources, limited time frame, and knowledge of the researches. More so, the database integrated in the OpenLCA software was only imported from European Life Cycle Database and Ecoinvent Association which are both outside the Philippines, this is because there are still no available Philippine – based database at the time of conducting the study

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2. Methods

Simulation Procedures

Simulation modeling is a technique for solving real-world problems in a safe and efficient manner. It provides an important method of analysis that is easily verified, communicated, and understood; as a result, the majority of LCA-based studies employ this approach. By providing clear insights into complex systems, simulation modeling provides valuable solutions to industries and disciplines.

The study undergoes a simulation procedure to efficiently determine and evaluate the process of LCA. This simulation study is important to also assess whether the input and output of EPS LWC are comprehensively considered. Likewise, a comparison between the outputs will be computed to provide valuable solutions.

Data Gathering

With the approval from the OPPES BPSU-MC, construction documents of the New CEA building were collected to use in this research. Data from these documents, specifically data with relation to EPS concrete, were broken down into subcategories.; extraction of raw material, transport of raw material, and production and packaging.

Inputs

Data gathered were inserted into the TRACI 2.1 database and OpenLCA app with labels of what kind of materials were used. Each material was pre-defined by the system and only needs the quantity being used in each of pre-classified phases/subcategories. This will be useful in the actual run of the system.

Treatment of Data

For the treatment of data, each input material was checked before the actual run. The system has its own calculation of impact these materials will bring to the environment. The test will only consume a couple of minutes depending on how much materials are to be digested. The result will be interpreted by the researchers.

Output Analysis

With help from recent studies, output was carefully analyzed to assess the environmental impact these materials may bring. There will be a comparison from other materials and other tools to compute the possible error of the said test. The analysis will be presented through a graphic with interpretation.

Simulation Graph

A simulation graph was constructed to represent the LCA process of EPS LWC. As shown in Figure 1, data gathered from raw materials–the weight in kilogram to be specific are needed as input for the system that will solve the environmental parameters. These materials

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are comprised of CSB, Portland cement, EPS, sand, and water which are also used to produce the EPS LCW. These materials are also supplemented with equivalent used raw materials and energy from extraction and production of each. These data from the production will be entered in OpenLCA Tool as data import that uses Ecoinvent and ELCD databases. Meanwhile, EPS LWC as an output product of the abovementioned materials will be entered as the production data assessing its life cycle with the New CEA Building as its case study. Then, data will be processed using TRACI 2.1 database. OpenLCA will release the results categorized as impact categories; human health impact, ecosystem quality, climate change, and resources that are also categorized with more specific environmental parameters.

In order to calculate the LCA of EPS LWC components, several parameters were taken into account. First, for the total environmental impact values of CSB, its assessment included the life cycle from energy generation and raw materials supply to the finished product in the factory gate, where the infrastructure and the production of the manufacturing facility is not considered. Second, since water comes from natural resources to artificially recharged wells, including the water supply network, heat, diesel, and power, there is no waste in its assessment. Third, Portland cement production involves electricity, heat generated, raw materials, infrastructure, transportation, ancillary products, and emissions, all of which are accounted for in its LCA. Fourth, the LCA of sand includes heat generation and raw material supply to the finished product on the factory gate. Fifth, EPS is synthesized by polymerizing styrene monomer, which is a chain growth reaction that is usually triggered by free radical organic initiators, and its LCA will include the energy inputs used during manufacture. And lastly, since fly ash is recycled from waste there is no environmental impact considered for its LCA.

Furthermore, the software calculates impact contributions at each stage of a product's life cycle. The number and type of impact categories will be determined by the user's choice of impact assessment method. Using the TRACI 2.1 methodology, the environmental impact categories calculated are Acidification, Carcinogenic, Ecotoxicity, Eutrophication, Fossil Fuel Depletion, Global Warming, Respiratory Effect, Noncarcinogenic, Ozone Depletion, and Smog.

To use the OpenLCA tool there are steps to follow after downloading and installing the application. The first step would be to create a new database and make sure that the local radio button is on to make data sharing and transfer easier. Then for the new database to be visible in the navigation pane, finish completing the reference data. Once the new database is created, the next step would be to download and import the life cycle inventory database and the impact assessment methods. The life cycle inventory database stores the input and output flows from various product systems, such as materials, energy, and emissions. The flows and flow properties are then used to create OpenLCA models and perform computations. Then, to generate a product system from process-based data, select the process system that corresponds to the issue. Click "create product system" in the general information tab, then

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"finish." In the reference tab, specify the functional unit and flow units for the study. To keep track of the assumptions, make note of it in the description tab. Once the product system is defined, the model graph tab will display only the reference process system. Followed by Right-click on the Product system, then Build Supply Chain, then Complete to build the whole life cycle model, including upstream contributions. After that, go to the product system and click "expand all" to see the whole supply chain. These connections can be modified based on the user's preferences and the system under investigation. Most process adjustments, editing, and deletion can be done in this window, depending on the nature of the problem. Finally, under the general information tab, click the "calculate" button, select the method of allocation, the impact assessment method, and the normalization or weighting set, and then click "calculate." In addition, to compare the LCA of the four different concrete it is necessary to create four different models following the steps discussed.

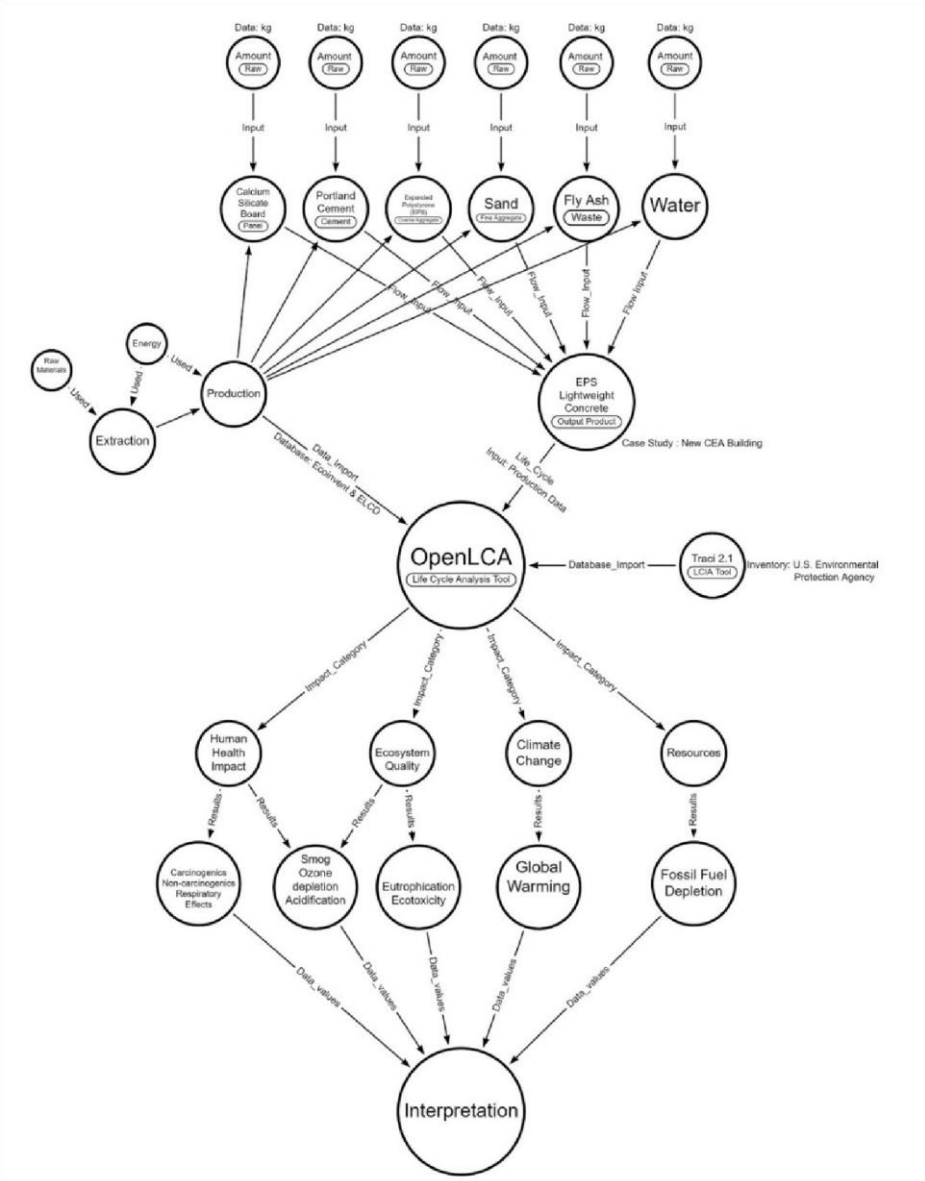

Figure 1

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Simulation Graph of OpenLCA using TRACI 2.1 database

Results

The cradle-to-gate result of EPS LWC LCA is shown in Table 1 which presents the total and distributed value of each environmental impact indicator for each material input of the product.

Table 1

Comparison of All Total Values of EPS Lightweight Concrete, Traditional Reinforced Concrete, CAB70 Lightweight Concrete and PET Concrete for Each Environmental Impact Category

	Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global Warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
	kg SO2	CTUh	CTUe	kg N eq	MJ surplus	kg CO2 eq	CTUh	kg CFC - 11 eq	kg PM 2.5 eq	kg O3 eq
EPS [total]	2.15E+01	1.81E-05	6.98E+02	2.57E+00	1.26E+03	6.86E+03	7.30E-05	9.27E-05	1.11E+00	1.93E+02
TRAD [total]	4.23E+01	4.31E-05	3.14E+03	2.01E+00	9.18E+03	1.03E+04	2.50E-03	2.89E-04	3.52E+00	3.84E+02
CAB70 [total]	5.09E+00	1.27E-05	6.67E+02	2.97E-01	4.31E+02	1.08E+03	1.41E-05	2.05E-06	2.77E-01	4.22E+01
PET [total]	8.78E+00	1.29E-05	4.79E+02	2.55E-01	5.66E+02	1.46E+03	1.35E-05	5.18E-05	4.21E-01	7.61E+01

Table 2

Result Of Expanded Polystyrene (EPS) Lightweight Concrete Life Cycle Assessment (LCA) Along with Distribution from Components to Total Environmental Impact Values

	Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global Warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
	kg SO2	CTUh	CTUe	kg N eq	MJ surplus	kg CO2 eq	CTUh	kg CFC 11 eq	kg PM 2.5 eq	kg O3 eq
EPS [total]	2.15E+01	1.81E-05	6.98E+02	2.57E+00	1.26E+03	6.86E+03	7.30E-05	9.27E-05	1.11E+00	1.93E+02
EPS beads	1.30E+01	8.90E-06	2.42E+02	2.20E+00	6.03E+02	4.81E+03	9.61E-06	2.25E-12	5.83E-01	1.02E+02
Portland cement	3.59E+00	7.21E-06	3.04E+02	1.10E-01	2.97E+02	7.64E+02	4.44E-06	4.50E-11	1.57E-01	2.93E+01
Sand	3.78E+00	3.23E-07	2.34E+01	1.33E-01	1.75E+02	4.54E+02	9.17E-06	7.74E-05	2.75E-01	4.76E+01
Calcium silicate board (CSB)	1.02E+00	6.94E-07	2.08E+01	7.23E-02	1.77E+02	8.23E+02	4.63E-05	1.53E-05	7.05E-02	1.37E+01
Tap water	7.20E-02	9.32E-07	1.07E+02	6.32E-02	1.07E+01	1.62E+01	3.47E-06	4.50E-11	2.68E-02	9.09E-01

Specifically, the potential environmental effects of the materials used in the production of EPS LWC shown in Table 2 can be interpreted as follows:

a. Cement – Cement is the most significant contributor to the environmental impact of all concrete mixtures (Gomes, 2020) because it emits a large amount of hazardous

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substances during the manufacturing process. As a result, manufacturers and environmentalists are looking for substitutes and additives to reduce the use of this material in the construction industry.

b. EPS beads – EPS beads is the main material in this concrete mixture because it gives the lighter weight feature. When compared to cement, EPS beads have a lower environmental impact. However, because it contains more material by volume, it will

outperform cement in terms of acidification, carcinogenics, eutrophication, fossil fuel depletion, global warming, respiratory effects, and smog.

c. Sand – Sand is also used in the traditional mixture as a concrete material. Sand reflects a significant amount of negative impacts following Portland cement in both traditional and EPS concrete specifically in ozone depletion.

d. Fly Ash – Fly ash is only an additive and is already considered as waste. As a result, it has no environmental impact in terms of construction material. It is likely that harmful substances were released during the manufacturing process, but as a construction material itself, fly ash can be considered an end product.

e. CSB – According to the LCA analysis result, CSB significantly contributes to the negative environmental impact of EPS concrete. With only 5% of the total volume of the concrete, it ranked first in non-carcinogenics with 4.6273500E-05 CTUh and second in global warming with 8.2265474E+02 kg CO2 eq and ozone depletion with 1.5268100E-05 kg CFC11eq impact assessments.

f. Water contributes least for most of the environmental impact except for ecotoxicity where it represents 15.33% (in EPS LWC).

Figure 2 presents the graphical representation of comparisons between the four (4) mix ratios used in the study. According to Figure 2, cement is the most significant contributor to the environmental impact of all concrete mixtures however it was reduced by 41.46% in EPS LWC compared to its average usage in traditional reinforced concrete. Also, EPS Beads is the main material in this concrete mixture because it gives the lighter weight feature, though EPS beads outperform cement because of its material composition.

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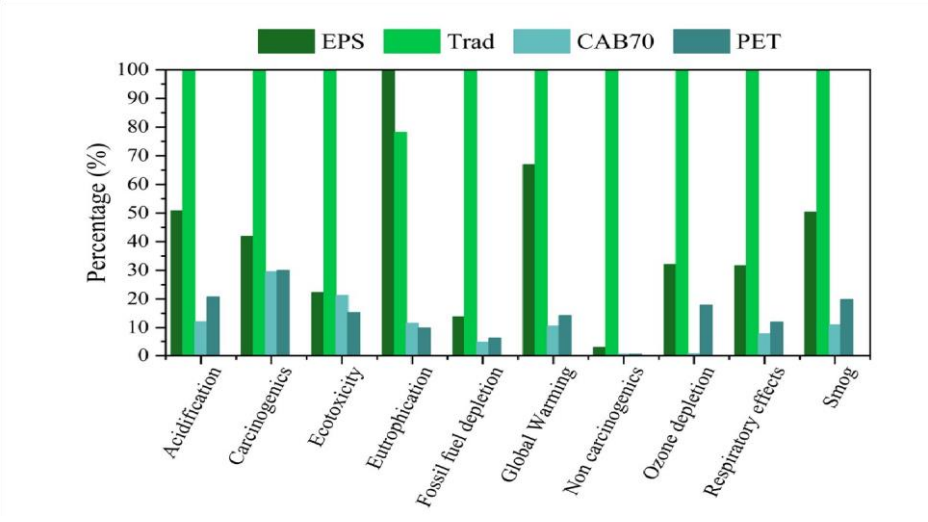

Figure 2

Comparison of All Total Values of EPS Lightweight Concrete, Traditional Reinforced Concrete, CAB70 Lightweight Concrete and PET Concrete for Each Environmental Impact Category

Due to the volume consumed by the EPS beads, the amount of sand in EPS LWC was reduced by 60.86%. Moreover, fly ash an additive that is considered as waste that has little to no environmental impact in terms of construction material. As for calcium silicate with only 5% of total volume, it is ranked first in non-carcinogenic and second in global warming and ozone depletion. In addition, water contributes least for most of the environmental impact except for ecotoxicity where it represents 15.33% (in EPS LWC).

Discussion

Except for eutrophication, EPS LWC has shown lower impacts than traditional reinforced concrete in all environmental impact categories. The results of the LCA between EPS LWC and traditional reinforced concrete showed an evident advantage in choosing EPS LWC as non-load-bearing wall replacement in terms of environmental sustainability. Furthermore, EPS beads are the most significant contributor to the negative environmental impact of EPS LWC, nearly doubling that of Portland cement. However, the addition of EPS beads results in the removal of more materials (such as concrete hollow blocks, steel rebar, and reinforced steel wire) from traditional reinforced concrete and nearly halving the amount of cement to be used. Steel rebar from traditional reinforced concrete is the most significant contributor to the negative environmental impact.

It can also be noted that reducing the percentage volume of EPS beads can have an impact on the overall environmental effects as it reversely increases the amount of cement, which also means an increase in negative impact.

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3. Conclusion and Recommendation

According to the results shown in the tables and figures above, it can be inferred that; (1) EPS LWC has an evident advantage in terms of environmental sustainability compared to traditional reinforced concrete, (2) despite EPS LWC qualification as concrete replacement to non-load bearing walls there are still existing replacements that are more environmentally sustainable, and (3) cement component of a concrete or LWC is the most contributing element for most of the environmental impact indicators followed by sand and aggregate.

With the above-mentioned results of the study, it is recommended to study the comparison of virgin and recycled expanded polystyrene (EPS) beads as aggregate for future LWC mix ratios. Also, it is recommended to find some other lightweight aggregates that may already be present in the market especially natural lightweight aggregates and aggregates that come from recycled products. Other than that, it is recommended that a comprehensive cradle to end of life is to be used for the future research study. furthermore, it is recommended to find other local databases that is within the country.

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